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Aeronautical Electronic and Electrical Laboratory

REPORT NO. NADC-EL-N6314

2 APR 1963

TECHNICAL NOTE  
AN INTRODUCTION TO ENVIRONMENTAL  
CHAMBER SYSTEMS ENGINEERING

Alvin R. Saltzman

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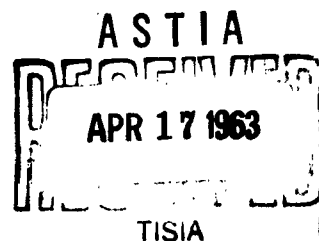
REPORT NO. NADC-EL-N6314 - TECHNICAL NOTE, AN INTRODUCTION TO  
ENVIRONMENTAL CHAMBER SYSTEMS ENGINEERING

Alvin R. Saltzman

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This technical note presents a discussion of the development and the studies required to obtain a systematic approach for environmental evaluations of an electronic system using environmental chambers to simulate specific environmental conditions or the transient environment of aircraft missions.

THIS TECHNICAL NOTE WAS ADAPTED BY THE AUTHOR FROM A PAPER PRESENTED AT THE NINTH NATIONAL SYMPOSIUM ON "RELIABILITY AND QUALITY CONTROL," SAN FRANCISCO, CALIFORNIA. THE OPINIONS EXPRESSED HEREIN DO NOT NECESSARILY REPRESENT THE VIEWS OF THE U. S. NAVAL AIR DEVELOPMENT CENTER.



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## S U M M A R Y

When thermal or other types of environmental cycles are performed in an environmental chamber for evaluating the reliability of an electronic equipment, the equipment, environmental chamber, its controllers, and other components form a part of and behave as an environmental chamber process system. Because of the complexity of modern environmental facilities and the need for reliable data simulating operational usage of electronic equipment, it is important that the "environmental process control engineer" obtain as much analytical information as possible on the environmental control capability of the chamber system before performing the actual evaluation.

This paper presents a systems engineering analytical method of evaluating the response of an environmental chamber system to a thermal environment step input. In addition, this paper presents the advantages and disadvantages of using alternatives for various types of control actions. Emphasis is placed upon the effect of the electronic equipment and other components of the system acting as thermal load disturbances to chamber environmental controllers.

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TECHNICAL NOTE  
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By Alvin R. Saltzman

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I N T R O D U C T I O N

In recent years the application of computers and automatic control systems for modern electronic weapons systems have increased tremendously. As the applications have increased, the demands placed upon the associated environmental systems have also increased and have taxed severely the ability of environmental designers to analyze existing systems or to synthesize new ones.

There has been a growing realization that before detailed design work is initiated, a thorough evaluation should be made of the environmental performance desired (particularly thermal), of the effectiveness with which the proposed system will accomplish the environmental task to be performed, and of the interrelations of the various portions of the proposed system. In view of the above, the need for a systems engineering approach to environmental problems is quite apparent.

P R O G R A M   F O R   E N V I R O N M E N T A L   S Y S T E M  
E V A L U A T I O N   O F   A V I O N I C S   E Q U I P M E N T

The Bureau of Naval Weapons has formulated a program of unit operations of environmental engineering,<sup>1,2</sup> as a basis for determining performance and acceptance of aeronautical electronic equipment systems for the fleet. This program is being implemented through the formulation of analytical and environmental specifications (such as thermal design Specification No. MIL-T-23103(WEP)<sup>3</sup>) which will require vendors of Navy aeronautical electronic equipment to prove that their equipment meets service requirements on a systems basis. A verification environmental specification and environmental report will also be required.

This paper deals with the development and the studies required to obtain a system approach for environmental evaluations of electronic systems using environmental chambers to simulate specific environmental conditions or the transient environment of aircraft missions.

1. Progress Report, Development of Cooling Specifications for Airborne Electronic Equipment, Report No. NADC-EL-59113
2. Saltzman, Alvin R. - Analytical and Environmental Cooling Specification for Airborne Electronic Equipment Aero/Space Engineering, Vol 19, No. 8, pp 38 to 42, August 1958
3. Spec No. MIL-T-23103(WEP), "Thermal Design Performance Evaluation, Airborne Electronic Equipment, General Requirement for"

Once the electronic equipment is in the chamber, it becomes part of an environmental chamber system process, and many questions about systems control need to be answered through systems analysis techniques before the tests are performed. These questions include:

1. Does the chamber, with the equipment in it, have sufficient capacity to provide the required simulated environmental conditions?
2. Are the controllers adequate to provide sufficient control of the chamber conditions during all transient environments with and without the electronic operating equipment?
3. Under what conditions or operations can the chamber control system use just on-off control?
4. When is proportional control alone required and, likewise, when are combinations of proportional rate and reset required?
5. When will certain control actions cause instability of the environmental process?
6. What are the inherent lags and time constants of the environmental chamber system, and how do these compare with actual aircraft compartment?
7. What types of lags or time constants could be added to the chamber system to provide better stability and control of environmental conditions?
8. Under what conditions will the electronic equipment act as a disturbance to the control system and cause oscillation and instability?

The analytical procedures for evaluating an environmental chamber process and determining the degree of accuracy that the chamber will follow the program, once tests are initiated, involves the developing of transfer equations that show interrelationships among the various components of the environmental process system. Because of the complexity of the system, it is difficult for many chambers to make this type of analysis. There is, however, a combination experimental and analytical method of sinusoidal analysis that has practical application and offers considerable simplification. The application of this technique is the main subject of this paper.

In 1923, H. Nyquist's theoretical treatment of feedback amplifiers utilized the response of components and systems to steady-state sinusoidal excitation, or frequency response as it is more usually called. This frequency response approach in combination with the Ziegler-Nichols process reaction curve technique (subsequently described) provides an important basis for handling environmental control problems. Sinusoidal response may be plotted in several ways. The rectangular plots of gain versus frequency and phase angle versus frequency are the most

4. Nyquist, H., *Bell System Technical Journal* 11, pp 126 to 147 (1932)

common. They are termed Bode plots. This type of plot will be used in the thermal environmental problem (subsequently defined) and the method of analysis will be called the "Zeigler-Nichols-Bode Method."

Zeigler-Nichols<sup>5</sup> on the basis of studies of a variety of systems, proposed that systems generally can be characterized by the apparent "dead time" and the maximum reaction rates of their transient responses.

Their method is primarily an experimental open-loop test of a system on manual operation. This open-loop test is used to determine the magnitude of the apparent dead time and apparent time constant. The closed loop is opened at a point immediately following the controller (figure 1), and the entire system is a steady state at the normal operating values of all variables. Generally the loop is cut, just after the controller mechanism, by employing the manual control apparatus. A step-change of the manipulated variable,  $m$ , is introduced and the result of this change is recorded at point,  $b$ , just before the controller. Thus, a step-change response is obtained for the open-loop system excluding the controller itself.

The recorded open-loop transient response is almost always an S-shaped curve, figure 1. The zero point of the step-change must be carefully marked. The open-loop response may be approximated by making the measurements shown by figure 1.

#### THE ZIEGLER - NICHOLS - BODE METHOD OF ANALYSIS

For an example, let us assume that a certain electronic equipment has reached the stage where its reliability has to be evaluated under rigid temperature environment specification requirements. As happens with many types of electronic equipments, this equipment does not operate continuously with power on (therefore with constant dissipation of heat), but on what is considered to be a cyclic operation. For this problem, a step function change of temperature is to be programmed into the chamber by a change of controller "set point" from 74° to 190° F. The problem to be solved involves determining the effect of certain types of controller actions on the actual response of a temperature environmental chamber to the thermal step input; also, the advantages and disadvantages of different types of controller actions (particularly on-off control versus combined proportional and reset control with regard to the response of the chamber), cycling characteristics, and effect of electronic thermal load disturbances are to be evaluated.

5. Zeigler, J. G., and Nichols, N. B., *Transactions American Society Mechanical Engineers*, pp 64, 759 (1942)

The analysis is initiated by placing the chamber on manual (open loop) operation and determining by the Ziegler and Nichols method the apparent dead time,  $L$ , and time constant,  $T$ , of the chamber system, figure 2.

Based upon the chamber as an open loop, analysis is made to determine closed-loop response with various types of control actions. Closed-loop response involves a feedback of the controlled variable to the summation component of the controller. The summation component provides a "deviation" from the controlled variable, which causes the controller to provide corrective action by varying the manipulated variable. This is the way the chamber operates on automatic control.

Operations are then directed toward determining the open-loop response without any control action of the chamber system as a function of frequency based upon the knowledge of chamber time constant,  $T$ , and dead time,  $L$ , obtained from figure 2. From the value of  $T$ , the corner frequency ( $1/T$ ) is determined. This and the knowledge that the response is "first order," are all that are required to draw the curve for magnitude ratio in decibels versus frequency. In a similar manner, knowing that the phase angle is 45 degrees at the corner frequency, the curve for phase angle,  $\theta$ , versus frequency is determined. A similar procedure is used to obtain the curves for magnitude ratio and phase angle versus frequency for dead time,  $L$ . Since the data given are in terms of db and  $\theta$ , the total db and  $\theta$  curves for  $T$  and  $L$  are obtained by simple addition, figure 3.

At a frequency beyond a phase angle,  $\theta$ , of 180 degrees, instability or cycling occurs as shown in figure 3. In brief, beyond a frequency corresponding to 180 degrees  $\theta$ , the environmental chamber control system is not stable and cannot be operated. To provide for situations where operation for various reasons is required at higher frequencies, various types of control actions can be incorporated into chamber controllers. In the following discussion, the relative effectiveness of control actions are presented for this particular problem. Since this paper is of an introductory nature, the four basic types of control actions are first described:

#### 1. Proportional Control

Proportional action is a mode of controller action where a continuous linear relation exists between values of the deviation,  $e$ , (figure 2) obtained with the closed-loop system and the manipulated variable,  $m$ . In the problem described herein, the manipulated variable is the power dissipated as heat by the heaters. The proportional sensitivity,  $K_c$ , is the change of manipulated variable,  $m$ , caused by unit change of deviation,  $e$ .

$$K_c = m/e \quad (1)$$



## 2. Reset Control

Reset action (also called integral control) is a mode of control where the value of the manipulated variable,  $m$ , is changed at a rate proportional to the deviation. Thus, if the deviation is doubled over a previous value, the final control element is moved twice as fast. Reset control follows the law of:

$$m = 1/T_1 \int edt + M \quad (2)$$

where  $m$  = manipulated variable

$T_1$  = integral time

$e$  = deviation

$M$  = constant of integration

The operational form of the equation is:

$$m = \frac{1}{T_1 S} e \quad (3)$$

The integral time,  $T_1$ , is defined as the time of change of manipulated variable caused by a unit change of deviation.

## 3. Proportional-Integral Control

Integral control action is often combined additively with proportional control action. The combination is termed proportional-integral action and is used to obtain certain advantages of both control actions. It is defined by the following differential equation:

$$m = K_c/T_1 \int edt + K_c e + M \quad (4)$$

## 4. Proportional-Rate Control

A rate control (also known as derivative control) may be added to proportional control action, and the combination termed a proportional-rate control action. A proportional-rate control action is defined by:

$$m = \underbrace{K_c e}_{\text{proportional}} + \underbrace{K_c T_d \dot{e}}_{\text{derivative}} + M \quad (5)$$

where  $T_d$  = derivative time

It is the simple addition of proportional-controller action and rate action as shown by the operational equation:

$$m - M = K_c(1 + T_d S)e \quad (6)$$

### 5. Proportional-Reset-Rate Action

The additive combination of proportional reset and rate actions is termed proportional-reset-rate action. It is defined by the differential equation:

$$\dot{m} = \frac{K_c}{T_1} e + K_c \dot{e} + K_c T_d \ddot{e} \quad (7)$$

or

$$m = \frac{K_c}{T_1} \int e dt + K_c e + K_c T_d \dot{e} + M \quad (8)$$

## ANALYSIS OF PROBLEM

Figure 3 shows that instability occurs at a phase angle of 180 degrees. Therefore, the ultimate frequency of operation shown on total  $\theta$  curve of figure 3 occurs at 0.78 radian/min (0.124 cycle/min). The ultimate period, which is the reciprocal of frequency, is calculated to be 8.1 minutes.

The ultimate proportional band, PBU, is an important criteria in determining the types of control actions required. It is defined as the percent input change per 100 percent output change at the ultimate frequency. The smaller the proportional band, the greater the gain of the system. Actual experience shows what ranges of proportional band are required for different types of control actions. For any value less than a proportional band of 2 percent, on-off control is reported in the literature as being acceptable. This percentage is, in effect, a measure of the overshoot from the set point value. Above 2 percent and up to 100 percent, deviations become relatively large, and various combinations of proportional rate-and-reset-control actions are required.

Figure 3 shows that the db shift for PBU is taken from the db curve for T as -44db at the ultimate frequency (180 degrees). This value of db converts to a PBU of only 6 percent. The overshoot is therefore less than 1° F for the step-function temperature change of +74° to 190° F. Thus, the rate of response period and amplitude are determined for on-off control.

If this were the only information required, the problem at this point might be considered complete. However, if the analysis, based upon a required environmental specification condition, were not satisfactory with the rate of response of the chamber using on-off control, and it was desired to evaluate the response of the chamber using proportional, rate, and reset controllers. To do this, a complete analysis would be required, relating the open-loop to closed-loop performance of the system and including the effect of thermal load disturbances inherent in the chamber or the electronic equipment.

One of the immediate objectives of the analysis which follows is to obtain the optimum combination of proportional and reset actions needed to provide "close" control for a wide range of disturbances without danger of instability. Close control is provided by as narrow a proportional band as possible with stability because the high gain of the narrow band causes a large correction for a small deviation. Control over a wide range of disturbances is provided when the 180-degree phase lag is obtained at as high a frequency as possible. Control without danger of instability is provided when there is an adequate spread between the 180-degree phase lag frequency and the frequency where the total gain, including that of proportional action, is 1.0; i.e., the db value is 0.

The spread of the 180-degree frequency and the 0-db frequency must be of the right amount and in the right direction to allow a margin of safety for a specific system represented by the frequency-response curves. The margin of safety depends upon both curves. For the final curves (control action included) the db value at the -180-degree frequency must be a safe distance from 0, and the phase angle at the 0-db frequency must be a safe distance from -180 degrees. Each of these distances has been given a specific name - "gain margin" and "phase margin." Experience obtained by the process industries shows that to maintain stability, the gain margin must not be less than 5 db and the phase margin must not be less than 40 degrees.

Margins within the range indicated previously are conservative and aimed to insure stability. Experience shows that the transient response curve for the measured variable (temperature within the chamber) after a step change in set point may be expected to cycle with about a one-quarter decay ratio.

The curves for gain (db) and phase angle ( $\theta$ ) for rate action are not shown on figure 3. However, these rate-control actions, when used, are added to total  $\theta$  and db curves. The overall effect is to increase the frequency range of operation before crossing the -180-degree phase angle. This is a basic purpose of rate action.

The overall effect of rate action is to provide in the closed-loop system a response with a lower amplitude of overshoot and a shorter cycling time. Space does not permit a detailed presentation of all the

steps involved in obtaining the curves shown in figures 3 and 4. However, these steps were discussed when the author presented this paper.

An important operation is to identify the frequency of  $-180$  degrees on the total  $\theta + \text{reset}$  curve, read the db value at that frequency, and compute the vertical shift required to make the db value equal the negative of the suggested gain margin (5 db). Then the complete db curve is shifted vertically by that number of decibels and the crossover frequency is found where the value is 0 db. This point is projected downward to the total  $\theta + \text{reset}$  curve and the phase angle is determined. If the phase angle is between  $-120$  to  $-140$  degrees, then that db rise identifies the required PBU. If not, a 4-to-1 attenuation of overshoot will not be obtained, and it is necessary to find a compromise position for acceptable phase and gain margin. Whatever the compromise, the gain must not be below 5 db.

#### RELATIONSHIP OF THE OPEN-LOOP TO CLOSED-LOOP RESPONSE

The final frequency-response curves for open-loop operation are shown on figure 3. The loop is not complete because the signal coming from the process block is not compared with the set point; in hardware terms, the controller is on manual operation. For a closed-loop system, the signal path connects the final control element, b, (figure 2) to the terminal of the summation component. For the complete control system, the loop must be closed by comparing the process block output with the set point. The comparison forms the deviation, e, which is then the input to the controller. The signal recirculates, and the loop is complete.

The open-loop analysis has been based on a recognition of what happens when the signal is recirculated. When the open-loop gain is 1.0 and its phase lag is  $180$  degrees for a signal, that signal will be propagated indefinitely if it is fed back into the controller. A standardized graph can be used to find the closed-loop curves once the open-loop curves are known. This graph is the Nichols plot<sup>6</sup> shown in figure 4. It contains two sets of coordinate curves plotted on one set of coordinates having values that can easily be read on the other. Figure 5 shows the db and phase-angle response of the open and closed loop with respect to frequency.

#### CLOSED-LOOP TRANSIENT RESPONSE

In general, the closed-loop frequency response curves of many process control systems resemble closely the curves of second order lags. Figures 6 and 7 show the represented curve shapes of magnitude degree of similarity to second order systems. In the plotting of these curves, the natural frequency is taken as the basic frequency point and is defined as having a value of 1.0 on the frequency scale.

6. *Control System Engineering* by Seifert, W. W., and Steeg, C. W., McGraw Hill Books Co., pp 189 (1960)

Figure 5 shows that the closed-loop db curve has a maximum rise of 0.5 db. From figure 6, a peak height of 0.5 db provides a damping factor of 0.6. The peak height for the curve with this damping comes at  $W_n$ , the natural frequency. In figure 5, the natural frequency,  $W_n$ , is at 0.18 rad/min. This corresponds to a frequency of 0.0285 cpm.

It is now possible to consider the problem and estimate the amount of cycling after a change in set point is made. The damping factor 0.6 determines how the output of a second order system will cycle after a step change input. The damping factor identifies the applicable curve shown in figure 7. The curve shows how the response will change in time, except that the horizontal scale has a product time and natural frequency,  $W_n t$ . Therefore, the curve is normalized, being the same for identical damping factors. To determine the actual response versus time, it is necessary only to divide  $W_n t$  by the natural frequency,  $W_n$ . The results are shown in figure 8. The response of the output for a given step input is now determined with the combination controller dial settings for reset and proportional control. This information is of considerable importance because it provides the environmental control engineer, before performing any tests, with information as to the suitability of the environmental chamber and its control actions in relationship to the environmental conditions that are to be programmed. Of equal importance is that the environmental engineer now has a basis for comparison of advantages and disadvantages of alternatives regarding various control actions in simulating the environmental conditions required.

The advantages and disadvantages are revealed from a review of data for simple on-off control versus the more complex (and expensive) combination of reset and proportional control actions. As indicated in figure 8, adding the reset and proportional control action actually causes an undesirable overshoot, calculated to be  $19^\circ \text{ F}$  (1.16), contrasted with less than  $1^\circ \text{ F}$  for on-off control. Another investigation<sup>7</sup>, revealed that on-off control is best suited for the control of single capacitance processes where process capacitance is large and dead time small. However, with reset and proportional action, the set point is reached in a shorter period of time.

#### EFFECT OF OFFSET

Offset or static error occur when the set point is changed from one value to another and the controlled variable does not exactly follow (figure 9); a steady deviation from the desired condition occurs. A low value of proportional band (high proportional sensitivity  $K_c$ ) reduces offset and decreases stabilizing time. For the particular temperature step change, the problem presented shows that there is a low percentage proportional band; therefore, on-off control from the point of view of "lining out" near zero deviation from the set point value was suitable.

7. *Automatic Process Control* by Eshman, D. P., John Wiley and Son, p 109 (1958)

When offset is a factor, reset control action defined by equation (2) is used primarily to eliminate this condition. Reset, defined in terms of repeats per unit of time, does what proportional action can not do; namely, line out at equilibrium at zero deviation from the set point.

When reset action is not employed, the amount of offset for any step change can be determined from the analytical procedure. The closed-loop db curve (figure 5) gives a graphical estimate of the amount of offset. Figure 5 shows that the closed-loop db curve levels off at zero as is required for reset-control action. For illustrative purposes, if reset-control action were not present and the closed-loop db curve leveled off at -1 db, the magnitude ratio would be valued at 89 percent. In other words, after a set point change from zero offset, the variable moves 89 percent of the way to the new set point.

#### EFFECTS OF DISTURBANCE SIGNALS OTHER THAN STEPS

The environmental analyst would like to know, before deciding upon his environmental chamber process system, whether any disturbances that are characteristic of the chamber or are caused by the electronic equipment will adversely affect the controller accuracy. For example, in the specific step-function temperature problem described herein, the analyst would want to consider whether the electronic equipment dissipating electrical power as heat in a cycling mode would cause any appreciable disturbance to the controller.

To evaluate the effects of the continuous cycling disturbance signals from which control systems normally suffer, the data of figure 10 gives the required db information. In the open loop, a cycling disturbance produces a cycling of the variable when the control variable is fixed at the position required to maintain the variable at a selected point. The difference between the variable and the selected point causes cycling and is in effect a deviation. Figure 2 is the block diagram of this operation. For a specific disturbance, the size-relation between the cycling of the disturbance signal and the cycling of the variable signal depends upon the disturbance frequency.

In the closed loop, where the control variable is readjusted by the controller, a cycling disturbance signal also produces a cycling of the deviation,  $e$ , which is the input to the controller whose output readjusts the value. The readjustment causes the deviation to cycle in a different way from the open-loop cycling. The relationship between the disturbance signal size and the deviation signal size is indicated by the closed-loop db curve, and is also dependent upon the frequency of the disturbance signal.

The difference between the open-loop and closed-loop db curves shows the effectiveness of the controller in making sure that the deviation signals are reduced in size to the extent that control is maintained at

required levels. The actual value of the deviation ratio is obtained by subtracting the db value of the open-loop curve at each frequency from the db value of the closed-loop curve (figure 5) and converting the difference to a "M" magnitude ratio.

The deviation ratio shows what effect the controller accomplishes. Unfortunately, it may develop that the controller for certain types of disturbances is actually doing harm by causing instability. Where the deviation ratio is less than 1.0, the controller makes the peak deviations less than they would be if a fluctuating signal were inserted in the loop and the measured variable were simply allowed to cycle as a result of such fluctuations. Where the deviation ratio is more than 1.0, the controller does harm because it makes the deviations larger than they would otherwise be. As shown in figure 10, controls incorporating proportional and reset are affected by equipment heat dissipating disturbances at certain frequencies.

Were the deviation is 1.0 or less, the controller does not affect the peak height of deviations. It is important for the environmental engineer to know, before initiating tests and selecting control actions, the nature of disturbances and whether these affect the control system.

## CONCLUSION

Nothing has had the same impact on the science or practice of engineering as have the transistor and the electronic computer upon the electronics field, or the supersonic jet aircraft and the ballistic rocket upon the field of aviation. In general, the chemical and mechanical industry has not been directly involved in the tremendous "technological cold war," which has been the daily product of companies in the electronics and aviation industries. The fact that the Ninth National Symposium on Reliability and Quality Control was held and that the scope of subject matter of various papers covered a broad range, provides evidence that the electronics industry requires the assistance of its sister industries in helping to provide reliability to the electronic system.

This paper is considered to be only of an introductory nature. It has presented one method of applying systems environmental engineering techniques and has covered a limited technical area. The problem of environmental systems engineering covers a broad range and involves many engineering sciences. Many of these problems involve nonlinear systems and require a much more sophisticated analytical and technical approach. Others require considerable more experimental data. Certain of these problems are the subject of investigations at the U. S. Naval Air Development Center, Johnsville, Pennsylvania.

## A C K N O W L E D G E M E N T

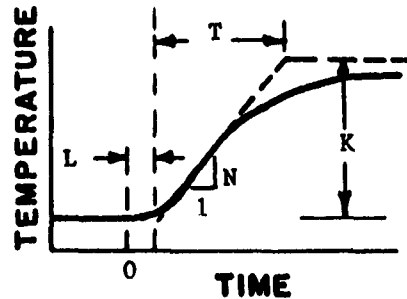
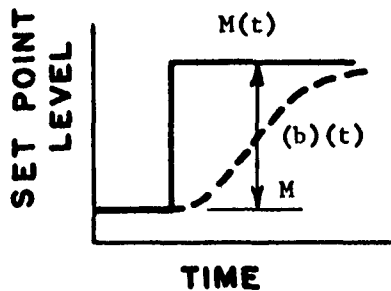
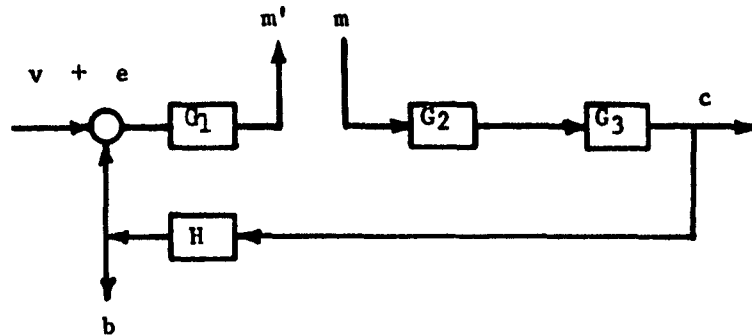
The method of frequency response originally proposed by Nyquist and its application by Bode have long been reported in various sources of technical literature. Likewise, the work of Ziegler and Nichols dealing with process reaction curves have been reported in the technical literature. The author combined these methods to provide an analytical method of evaluating performance of environmental chambers containing electronic equipment. In combining the individual procedures, the author was particularly influenced by the book of G. K. Tucker and D. M. Wills<sup>8</sup> in their presentation of Bode frequency response.

Alvin R. Saltzman  
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8. *A Simplified Technique of Control System Engineering* by Tucker, G. K., and Wills, D. M.





# ELEMENTS

$G_1$	Controller
$G_2$	Final control element
$G_3$	Process
H	Feedback element

# VARIABLES

v	Set point
e	Activating signal
m	Manipulated variable
c	Controlled variable (temperature)
b	Feedback variable
$M(t)$	Magnitude of change in units of variable being changed
L	Dead time
N	Reaction rate in units per time
K	Magnitude of change in units of recorded variable (temperature)

FIGURE 1 - Open-Loop Transient Test

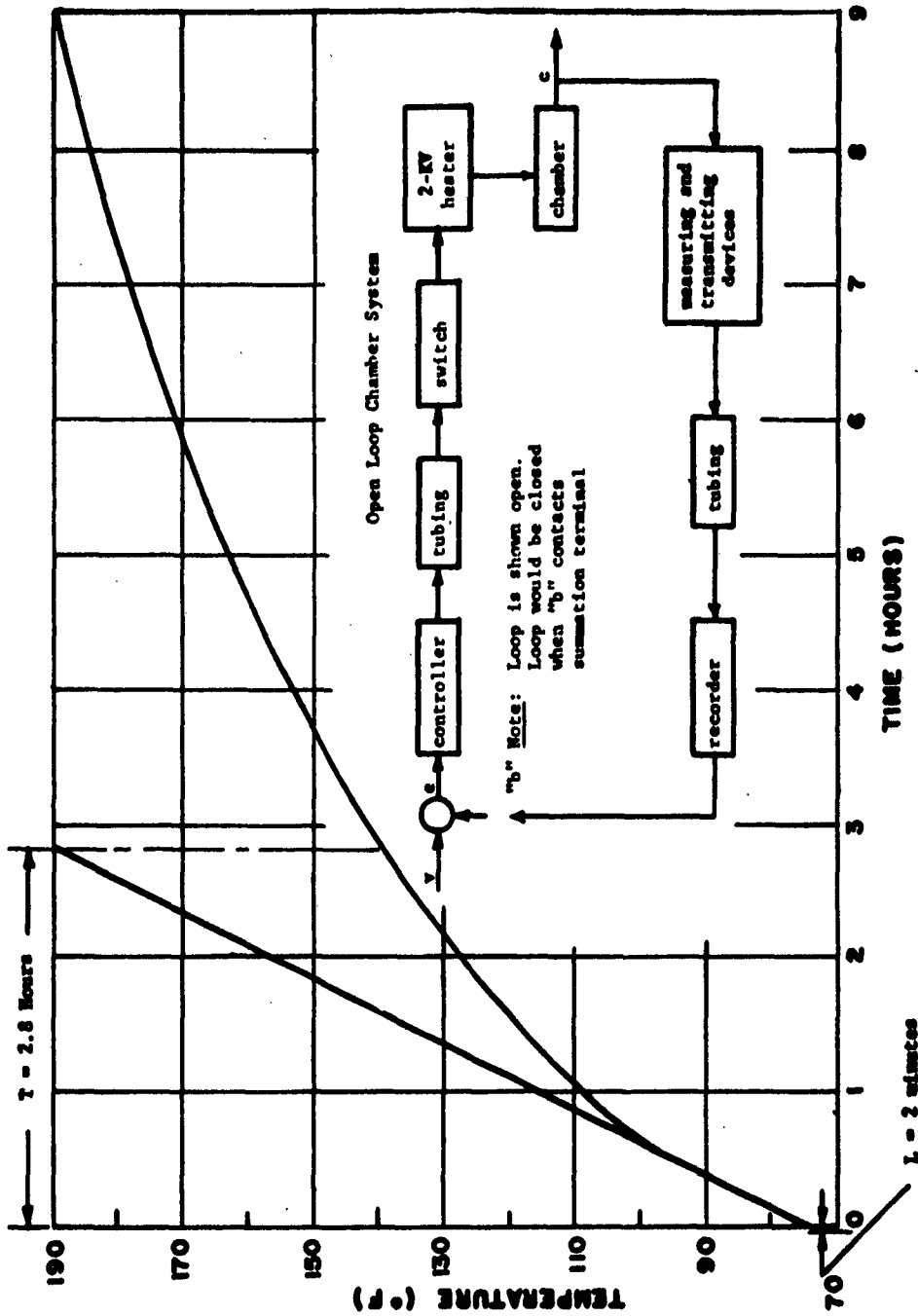
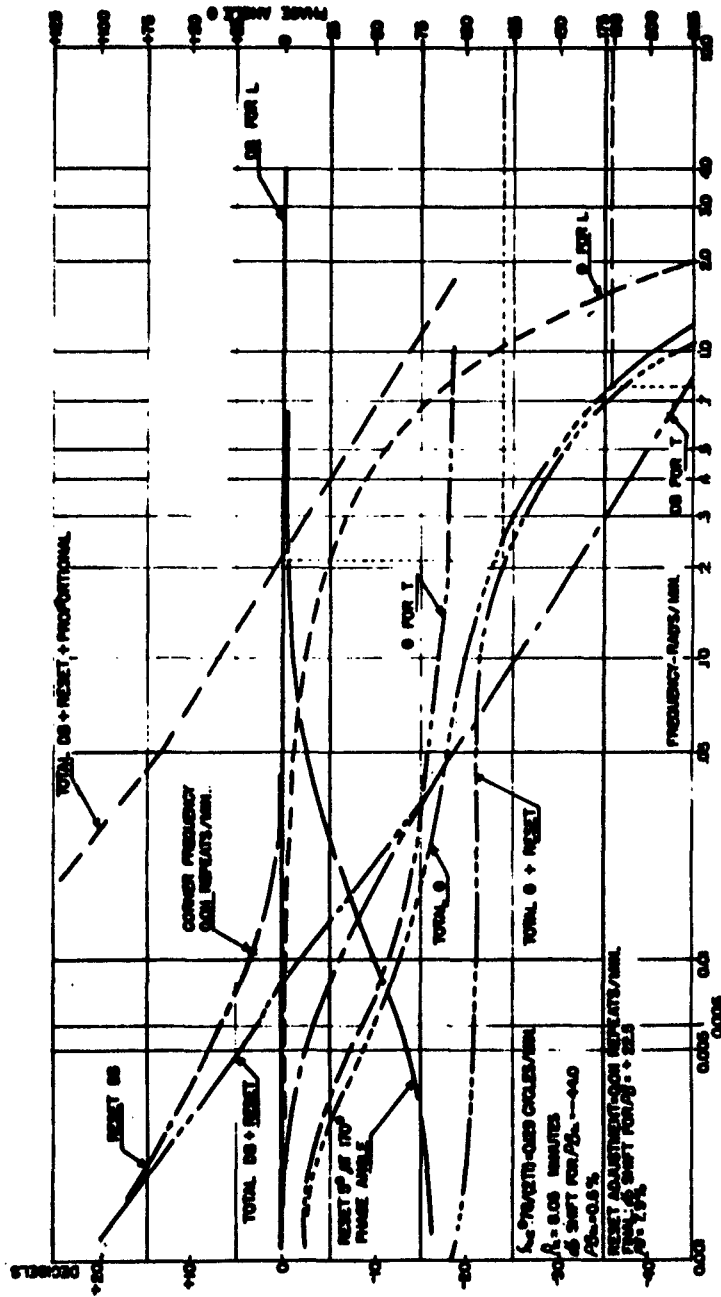


FIGURE 2 - Environmental Chamber Temperature Response to 2-kw Heat Input



**FIGURE 3 - Reset and Proportional Band Adjustments for Chamber Control System**

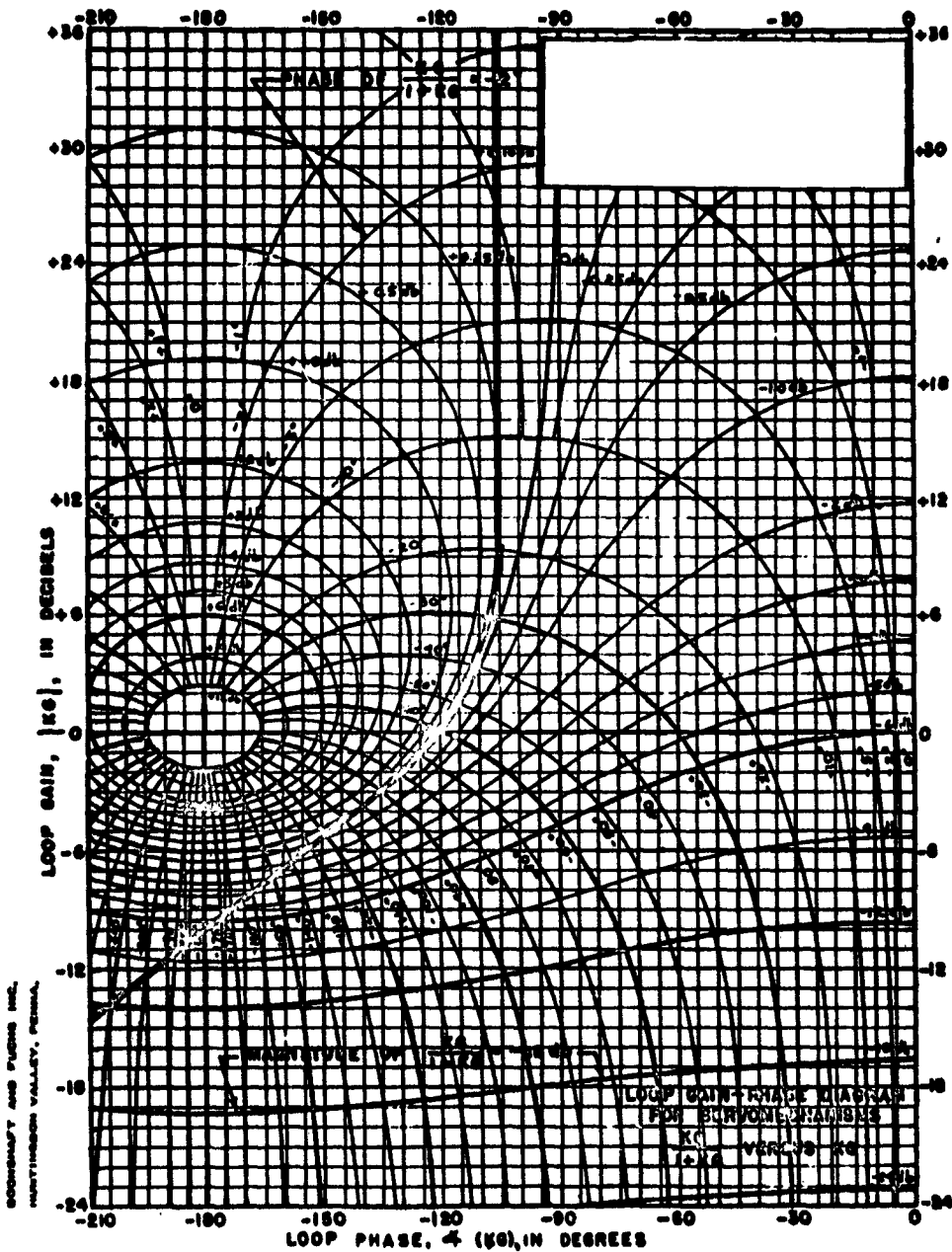


FIGURE 4 - Nichols Chart of Temperature Control System

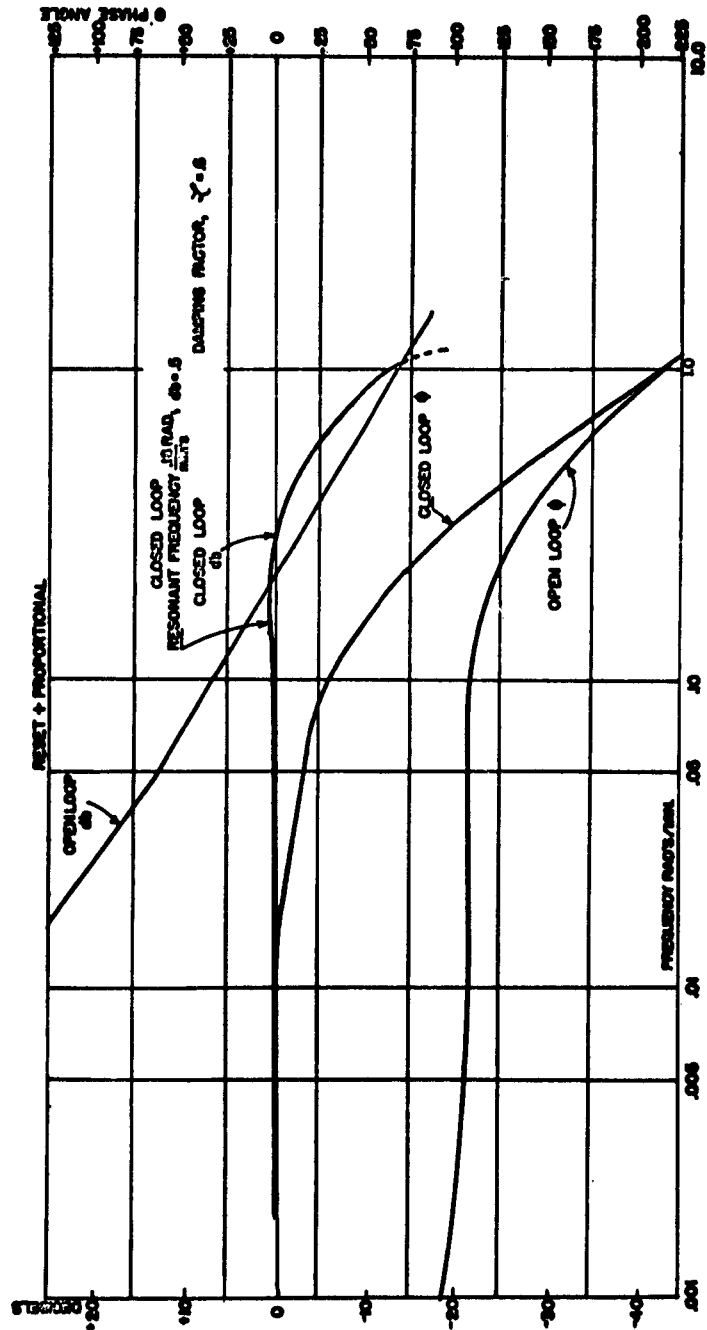


FIGURE 5 - Closed-Loop and Open-Loop Responses of Temperature Control System

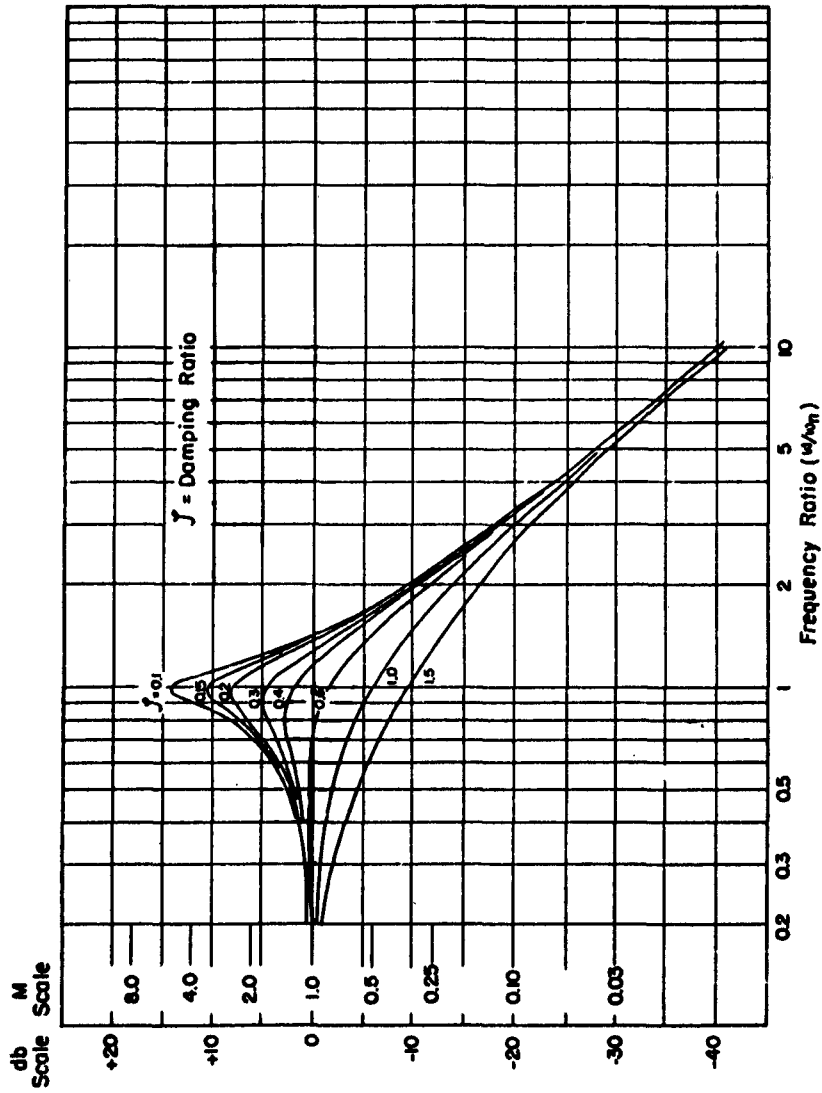


FIGURE 6 - Frequency Response of Second Order Systems

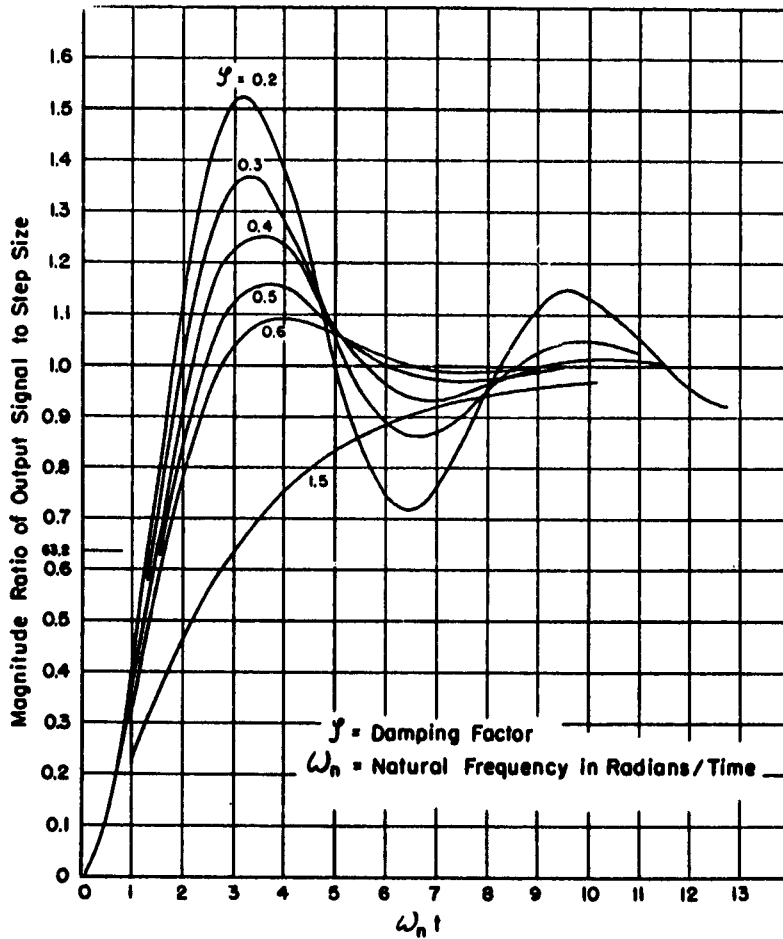


FIGURE 7 - Magnitude Ratio Versus  $\omega_n t$

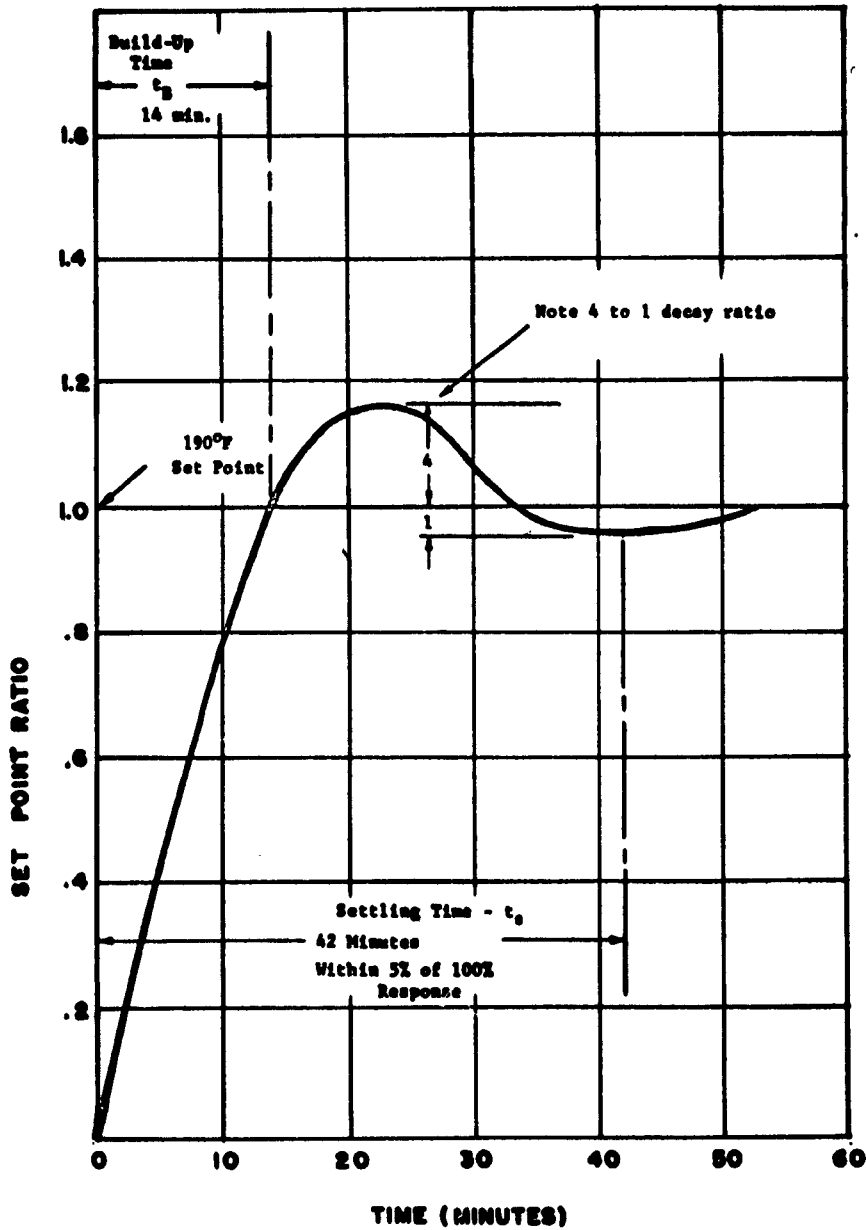


FIGURE 8 - Closed-Loop Cycling Response to Step Input  
(Proportional-Reset Control)



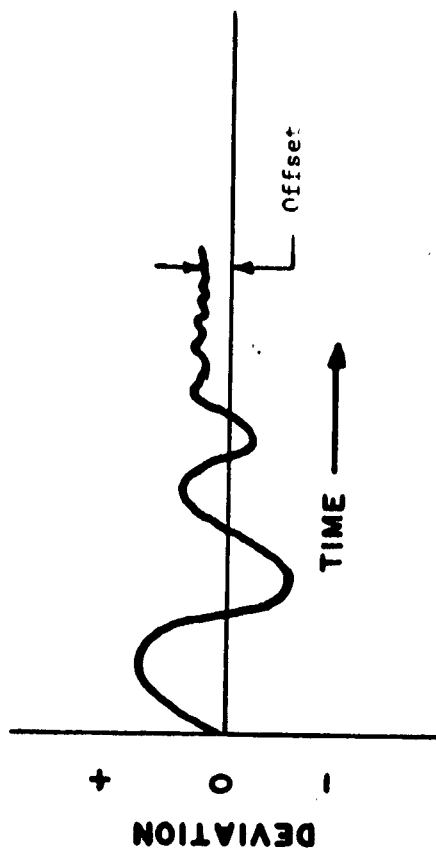


FIGURE 9 - Illustration of Offset

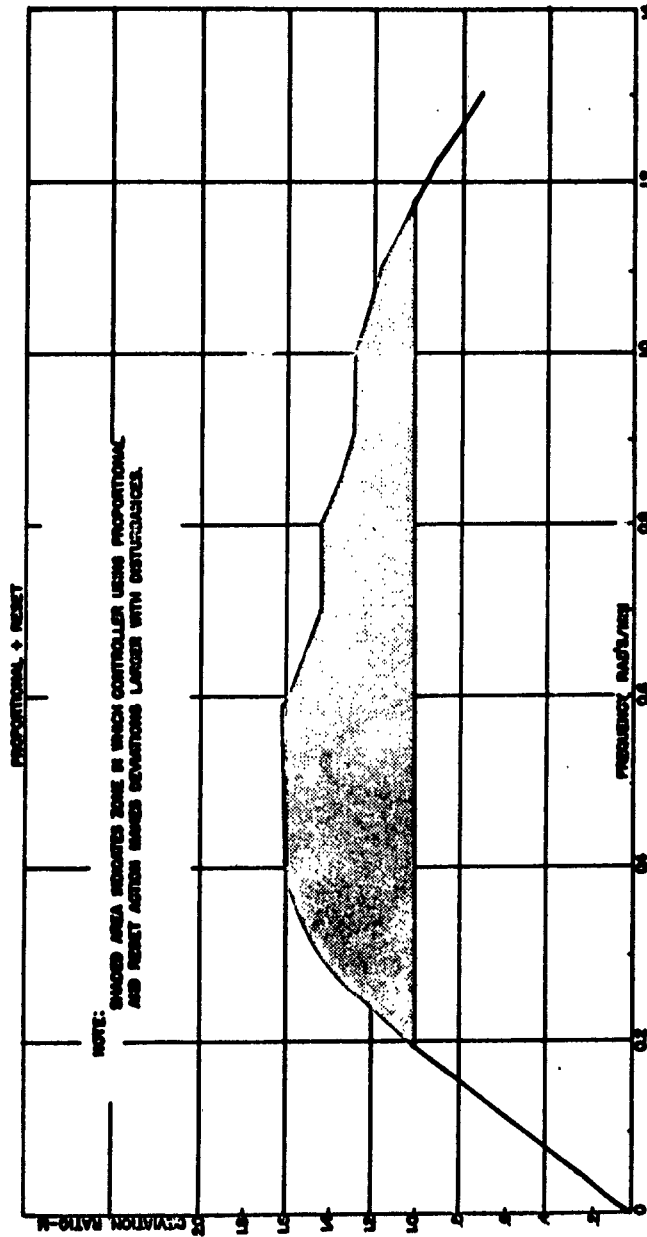


FIGURE 10 - Deviation Ratio Versus Frequency

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